

LHC/ILC Interplay in SUSY Searches

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Abstract. Combined analyses at the Large Hadron Collider and at the International Linear Collider are important to reveal precisely the new physics model as, for instance, supersymmetry. Examples are presented where ILC results as input for LHC analyses could be crucial for the identification of signals as well as of the underlying model. The synergy of both colliders leads also to rather accurate SUSY parameter determination and powerful mass constraints even if the scalar particles have masses in the multi-TeV range.

1. LHC/ILC interplay in the gaugino/higgsino sector

Supersymmetry (SUSY) is one of the best-motivated candidates for physics beyond the Standard Model (SM). If experiments at future accelerators, the Large Hadron Collider (LHC) and the International Linear Collider (ILC), discover SUSY they will also have to determine precisely the underlying SUSY-breaking scenario. Methods to derive the SUSY parameters at collider experiments have been worked out, for instance in [1, 2, 3, 4, 5].

1.1. Mass predictions for the heavy gauginos/higgsinos

In [4, 6] it has been studied in detail for a representative SUSY scenario SPS1a [7] how results at the ILC can benefit from LHC input and vice versa.

LHC analysis: In most cases the masses of the Susy particles can only be studied by analysing complicated decay chains, like

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{\ell}_R^\mp \ell^\pm q \rightarrow \tilde{\chi}_1^0 \ell^\mp \ell^\pm q, \quad (1)$$

which might be difficult to resolve. The precise reconstruction of the states in the decay chains requires in particular the knowledge of the mass of the lightest Susy particle (LSP), which is often assumed to be stable. In SPS1a the second lightest neutralino can be identified in the opposite sign-same flavour signal (OS-SF) with an uncertainty of about $\delta m_{\tilde{\chi}_2^0} = 4.7$ GeV. To measure the heavier gauginos/higgsinos is extremely challenging due to mass degeneration.

ILC analysis: Precise simulations for the mass measurements of the sleptons and the light charginos and neutralinos show that an accuracy of much less than 1 GeV can be achieved at the ILC with $\sqrt{s} = 500$ GeV. Particularly interesting is the high accuracy in the determination of $m_{\tilde{\chi}_1^0}$ with $\delta(m_{\tilde{\chi}_1^0}) = 0.05$ GeV from \tilde{e}_R decays, but also the accuracy $\delta(m_{\tilde{\chi}_1^\pm}) = 0.55$ GeV and $\delta(m_{\tilde{\chi}_2^0}) = 1.2$ GeV are important.

It has been assumed that the cross sections for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ have been precisely measured at different energies $\sqrt{s} = 400, 500$ GeV and for different beam polarizations (P_{e^-}, P_{e^+}) = ($\pm 80\%, \mp 60\%$) [8].

LHC/ILC interplay analysis: Putting together all results from LHC and ILC allows to determine precisely the fundamental electroweak parameters in the minimal supersymmetric standard model (MSSM), M_1 , M_2 , μ and $\tan\beta$, without any assumption on the SUSY breaking scheme. The masses of the heavy neutralinos and charginos can now be predicted. Concerning again studies at the LHC such mass predictions from the ILC analysis lead to an increase of statistical sensitivity, which could be crucial for the search for statistically marginal signals: Together with a precise knowledge on the mass of the lightest stable particle $\tilde{\chi}_1^0$ and the light slepton masses measured at the ILC, the mass predictions lead to a clear identification of the dilepton edge from the $\tilde{\chi}_4^0$ decay chain, followed by precise mass measurements of these heavy particles, cf. Fig. 1. Measuring the heavy particles right at the predicted masses provides an important check of the underlying Susy model.

1.2. Model distinction between MSSM and NMSSM

Such an important model check has been studied in detail in [9], where two basic supersymmetric models, the MSSM and the next-to-minimal supersymmetric standard model (NMSSM) have been analyzed. The NMSSM [10] is the simplest extension of the MSSM by an additional Higgs singlet field. The corresponding additional fifth neutralino may significantly change the phenomenology of the neutralino sector due to the suppressed coupling to ordinary gauge bosons of the singlino admixture [11].

In this case study a scenario has been presented where all kinematically accessible neutralinos and charginos have similar masses and almost identical cross sections, within experimental errors, in MSSM and NMSSM. Although the second lightest neutralino in the NMSSM has a significant singlino component, the models cannot be distinguished by the experimental results at the LHC or at the ILC₅₀₀ with $\sqrt{s} = 500$ GeV alone if only measurements of masses, cross sections and gaugino branching ratios are considered. Also the Higgs sector does not allow the identification of the NMSSM. Precision measurements of the neutralino branching ratio into the lightest Higgs particle and of the mass difference between the lightest and next-to-lightest SUSY particle may give first evidence for the SUSY model but are difficult to realize in our case. Therefore the identification of the underlying model requires precision measurements of the heavier neutralinos by combined analyses of LHC and ILC.

Although the neutralinos $\tilde{\chi}_{2,3}^0$ have significant singlet components of about $> 42\%$ in the NMSSM, the masses of the accessible light neutralinos and charginos, as well as the production cross sections, lead to identical values in the two models within experimental errors.

LHC/ILC analysis: As described in the previous section, the interplay analysis at both colliders allows to determine the fundamental parameters M_1 , M_2 , μ and $\tan\beta$ with high precision. The parameters lead within the assumed experimental uncertainty to predictions for the heavy neutralinos and their mixing character: the MSSM predicts an almost pure higgsino-like state for $\tilde{\chi}_3^0$ and a mixed gaugino-higgsino-like $\tilde{\chi}_4^0$, see Fig. 2. However, such a prediction of the mixing character contradicts the outcome of the LHC, where only neutralinos with a sufficiently high gaugino admixture can be resolved: $m_{\tilde{\chi}_3^0} = 367 \pm 7$ GeV. Such a contradiction leads obviously to the correct identification of the supersymmetric model.

2. LHC/ILC results for unravelling multi-TeV scalar fermions

Scenarios where the squark and slepton masses are very heavy (multi-TeV range) are particularly challenging. In most studies to determine the fundamental SUSY parameters, it has been assumed that the masses of the virtual scalar particles are already known. In the case of heavy scalars such assumptions, however, cannot be applied. It has been shown in [12, 13] that via exploiting spin effects [14], useful indirect bounds for the mass of the heavy virtual particles could be derived from forward-backward asymmetries of the final lepton $A_{\text{FB}}(\ell)$.

In [13] a case study with ~ 2 TeV scalar particles sector is discussed: $m_{\tilde{\chi}_{1,2}^\pm} = 117,552$ GeV, $m_{\tilde{\chi}_{1,2,3,4}^0} = 59,117,545,550$ GeV, $m_h = 119$ GeV, $m_{\tilde{g}} = 416$ GeV and $m_{\tilde{\nu}_e}, m_{\tilde{e}_{R,L}} \sim 2$ TeV $m_{\tilde{q}_{R,L}} \sim 2$ TeV.

Analysis at the LHC: All squarks in this scenario are kinematically accessible at the LHC. However, since $m_{\tilde{q}_{L,R}} \sim 2$ TeV, precise mass reconstruction will be difficult. Since the gluino is rather light in this scenario, several gluino decay channels can be exploited. The largest branching ratio is a three-body decay into neutralinos, $BR(\tilde{g} \rightarrow \tilde{\chi}_2^0 b \bar{b}) \sim 14\%$, followed by a subsequent three-body leptonic neutralino decay $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-)$, $\ell = e, \mu$ of about 6%. The mass difference between the two light neutralino masses can be measured from the dilepton edge with an uncertainty of about $\delta(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) \sim 0.5$ GeV [6, 15]. It is expected to reconstruct the gluino mass with a relative uncertainty of $\sim 2\%$ [16].

Analysis at the ILC: At the first stage of the ILC, $\sqrt{s} \leq 500$ GeV, only light charginos and neutralinos are kinematically accessible. However, in this scenario the neutralino sector is characterized by very low production cross sections, below 1 fb, so that it might not be fully exploitable [13]. Only the chargino pair production process has high rates and $\sqrt{s} = 350$ and 500 GeV are used. The chargino mass can be measured in the continuum, with an error of about 0.5 GeV, optimized via threshold scans to $m_{\tilde{\chi}_1^\pm} = 117.1 \pm 0.1$ GeV [17].

The mass of the lightest neutralino $m_{\tilde{\chi}_1^0}$ can be derived, either from the lepton energy distribution ($BR(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell) \sim 11\%$ or from the invariant mass distribution of the two jets ($BR(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 q d \bar{q}_u) \sim 33\%$: $m_{\tilde{\chi}_1^0} = 59.2 \pm 0.2$ GeV [17]. Together with the information from the LHC a mass uncertainty can be assumed for the second lightest neutralino of about $m_{\tilde{\chi}_2^0} = 117.1 \pm 0.5$ GeV. The dominant SM background is W^+W^- production. For the semileptonic (slc) final state, this background can be efficiently reduced from the reconstruction of the hadronic invariant mass. An overall selection efficiency of 50% in the fully leptonic and semileptonic final states has been estimated. Statistical uncertainties for the cross section and A_{FB} (see [13]) based on $\mathcal{L} = 200 \text{ fb}^{-1}$ in each polarization configuration, $(P_{e-}, P_{e+}) = (-90\%, +60\%)$ and $(+90\%, -60\%)$, and a relative uncertainty in the polarization of $\Delta P_{e\pm}/P_{e\pm} = 0.5\%$ [8] have been taken into account.

Parameter determination in LHC/ILC interplay:

The underlying SUSY parameters are determined in two steps:

- a) only the masses of $\tilde{\chi}_1^\pm, \tilde{\chi}_1^0, \tilde{\chi}_2^0$ and the chargino pair production cross section, including the full leptonic and the semileptonic decays have been used as observables. A four-parameter fit has been applied for the parameters M_1, M_2, μ and $m_{\tilde{\nu}_e}$ for fixed values of $\tan \beta = 5, 10, 15, 20, 25, 30, 50$ and 100. Due to the strong correlations among parameters [13], fixing $\tan \beta$ is necessary. A χ^2 test has been performed and one obtains:

$$59.4 \leq M_1 \leq 62.2 \text{ GeV}, \quad 118.7 \leq M_2 \leq 127.5 \text{ GeV}, \quad 450 \leq \mu \leq 750 \text{ GeV}, \\ 1800 \leq m_{\tilde{\nu}_e} \leq 2210 \text{ GeV}.$$

- b) the leptonic forward-backward asymmetry has been included as additional observable, exploiting full spin correlations between production and decay [14]. Only the semileptonic and purely leptonic decays were considered. The $SU(2)$ relation between the two virtual masses $m_{\tilde{\nu}}$ and $m_{\tilde{e}_L}$ has been applied.

The multiparameter fit strongly improves the results. No assumption on $\tan \beta$ has to be made. The results are

$$59.7 \leq M_1 \leq 60.35 \text{ GeV}, \quad 119.9 \leq M_2 \leq 122.0 \text{ GeV}, \quad 500 \leq \mu \leq 610 \text{ GeV}, \\ 14 \leq \tan \beta \leq 31, \quad 1900 \leq m_{\tilde{\nu}_e} \leq 2100 \text{ GeV}.$$

Mainly the constraints for the mass $m_{\tilde{\nu}_e}$ are improved by a factor of about 2, see Fig. 3, and for gaugino mass parameters M_1 and M_2 by a factor of about 5. The higher masses are predicted to be within the ranges $506 < m_{\tilde{\chi}_3^0} < 615$ GeV, $512 < m_{\tilde{\chi}_4^0} < 619$ GeV, $514 < m_{\tilde{\chi}_2^\pm} < 621$ GeV.

Scenarios with heavy scalar particles are challenging for determining the MSSM parameters. The forward-backward asymmetry is a powerful observable and strongly dependent on the mass of the exchanged heavy particle. If the $SU(2)$ constraint is applied, the slepton masses can be determined to a precision of about 5% for masses around 2 TeV at the ILC running at 500 GeV. One should note that the analysis is performed entirely at the EW scale and without any reference to the underlying SUSY-breaking mechanism.

3. Conclusions

LHC/ILC synergy can be crucial for resolving SUSY signals of heavy particles, determining the underlying SUSY model and fixing the fundamental parameters. Even challenging scenarios where neither the LHC nor the ILC alone can provide the needed data, the combined analysis of both colliders is expected to be successful. The high precision measurements allow to determine the parameters very accurately, leading to powerful mass predictions of the heavier particles. Even scenarios with multi-TeV sparticles can be resolved. Such predictions might become crucial for outlining the higher energy steps of the ILC.

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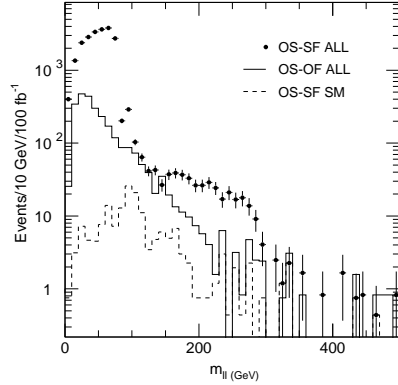


Figure 1. The invariant mass spectrum of the heavy neutralino/chargino decay chains. The dilepton opposite-sign-same-flavour lepton edge of $\tilde{\chi}_4^0$ is the edge between $200 \text{ GeV} < m_{\ell\ell} < 400 \text{ GeV}$ [4, 6].

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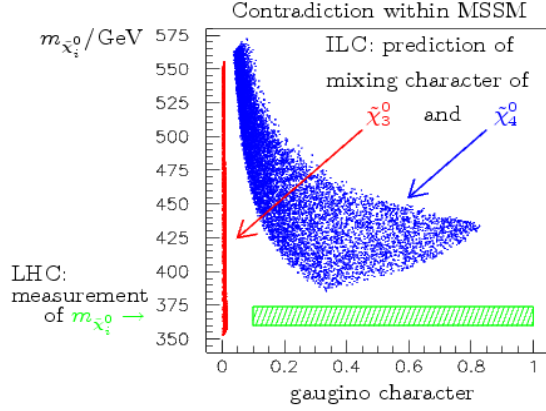


Figure 2. Predicted masses and gaugino admixture for the heavier neutralinos $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$ within the parameter ranges consistent at the ILC₅₀₀ analysis in the MSSM and a measured mass $m_{\tilde{\chi}_i^0} = 367 \pm 7$ GeV of a neutralino with sufficiently high gaugino admixture in cascade decays at the LHC. We took a lower bound of a detectable gaugino admixture of about 10% [9].

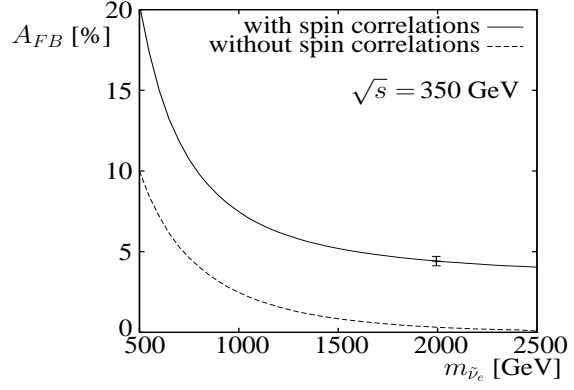


Figure 3. Forward-backward asymmetry of e^- in the process $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\ell^-\bar{\nu}$, shown as a function of $m_{\tilde{\nu}_e}$. For nominal value of $m_{\tilde{\nu}_e} = 1994$ GeV the expected experimental errors are shown. For illustration only, the dashed line shows that neglecting spin correlations would lead to a completely wrong interpretation of the experimental data [13].

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